ION INJECTORS FOR SINGLE- AND TWO- PHASE ELECTROGASDYNAMIC GENERATORS

by

William Taylor Ober

United States
Naval Postgraduate School

THESIS

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William Taylor Ober II
Lieutenant (junior grade), United States Navy
B. S., United States Naval Academy, 1968

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ABSTRACT

Systems suitable for the injection of ions into electrogasdynamic (EGD) generator devices were built and tested. The mechanism of injection was based on a corona discharge, whereby ions moving through an electric field can be intercepted by a gaseous flow. The intercepted ions are of one polarity, insuring selective ion injection. Two types of injector units were investigated. One was a molecular ion device which produced ions directly from the carrier gas, and the other created larger sized ions, resulting in an aerosol flow. The latter consisted of passing saturated steam through a corona discharge and injecting it into an air stream. In order to aid the injection process, the wake of a cylinder in the air stream was utilized in both cases. Most of the work done here was devoted to the design and testing of the aerosol flow device. The degree of success was moderate.

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LIST OF SYMBOLS AND ABBREVIATIONS

E_b	electric field strength
EGD	electrogasdynamic
I_C	corona current
I_G	generator current
I-V	current-voltage
L	length
V_C	corona voltage
v_D	charged particle drift velocity
μ	charged particle mobility
W	mass flow rate
A*	nozzle exit area for choked flow
k	C_p/C_v
R	steam gas constant
P_o	pressure
T_o	temperature

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I. INTRODUCTION

The principle of operation of an electrogasdynamic (EGD) generator is based on the fact that if a moving gas can displace ions away from their point of creation it can perform electrical work. The generator, therefore, consists of an ion injector, a conversion region (where the ion migration path is influenced by the direction of the gas flow), and a collector device to pick up the ions which have been carried downstream. Of these three basic components, the ion injector is the most complex and critical to the proper operation of the generator. The purpose of this work was to design and test two means of ion injection, classified by the nature of the ions desired in each case. The first injects molecular air ions into an air stream. The second one injects ionized water droplets into the air stream; this injection method will be alternately referred to as either a colloidal ion suspension or an aerosol flow.

The problem of creating an efficient EGD generator has been studied with considerable interest over the past seven years[1-5]. It was decided at the start of this project to employ a cylinder mounted spanwise in a subsonic test section to generate a two dimensional turbulent wake. It was thought that this wake would facilitate the removal of charged particles from their generation point and thus aid the process by which the air flow forces them downstream to a collector device. With this goal in mind all designs for the generation and injection of charged particles were incorporated with the cylinder. It was also felt that the turbulent wake would be instrumental in delaying electrical breakdown of the carrier gas.

Preliminary studies revealed that a corona discharge device would provide the most suitable means of ion injection because of the relatively high (atmospheric) pressures involved in the air flow in the cylinder wake[6,7]. The characteristics of a corona discharge which make it a favorable injector are given below.

One type of corona can be created when a sufficient voltage is placed across the gap between a circular ring and a centrally mounted needle tip. At voltages below that required to cause an arc discharge across the gap there exists a field of sufficient strength to ionize the gas in this region. The charges of polarity opposite to that of the tip are then trapped in a charge sheath about the needle tip. The effect of this sheath is to reduce the outer electric field strength. This fact when simply stated means that although a current still exists due to the migration of charges of the same polarity as the needle toward the ring, the migration occurs in a field of weakened strength and these ions can be more easily removed from the influence of this field. Thus, particles of a desired polarity can be forced away from the electric field of the corona unit (See Figure I).

II. MOLECULAR ION EXPERIMENTS

Preliminary work with molecular ions involved a study of the current voltage characteristics of a corona discharge unit which consisted of an aluminum ring mounted in a teflon block and a needle tip shaped from an iron nail (see Figure II). Current-voltage (I-V) curves from this setup are shown in Figure II. It was learned from this test that any sharp edges in the ring will act as discharge points, and therefore would cause the unit to deviate from its desired operational characteristics. It was also found that the position of the needle tip within the ring has a noticeable effect on the I-V characteristics. The test was also employed as a familiarization period on the safety requirements of high voltage work.

From this point the study was divided into two phases. Phase one involved the design and study of a small corona unit to be incorporated with the aforementioned cylinder. The cylinder was mounted in a test section through which air flowed at velocities in the vicinity of three hundred feet per second. In this phase then, the corona unit was employed to ionize air and the air flow would provide a carrier which would force some of the ions out from the inside of the ring and downstream to a collector.

For a drawing of the model chosen for this phase refer to Figure III. The ring was designed to be of a size which would insure that the whole unit would be within the wake of a one centimeter diameter cylinder. Braces on the ring attached it to the downstream side of the cylinder and the needle tip wire was placed through a hole drilled streamwise through the cylinder. Electrical leads were brought in through the test section

walls in such a manner as to provide contact with ring and needle at the ends of the cylinder.

If the needle were positively charged, positive air ions would migrate toward the ring, which would be at ground potential. As stated earlier, the migration would occur in a region of weak field strength due to a sheath of negative ions held in the vicinity of the needle tip. Thus for this polarity it should be possible in theory to remove some of these positive ions from this field by means of the air flow before they reach the ring. Similarly, electrons could be generated and removed by simply reversing the polarity of the device.

Initial tests were then made to determine I-V characteristics of the unit in stagnant air. These are shown for either polarity in Figure IV. The next series of tests involved taking I-V data with the cylinder and corona unit mounted in the test section with various air flow rates. The electrical and metering setup is shown in Figure V. At this point it was determined that our I-V data was not a true indication of what was happening within the corona unit. The wiring was crude at best and at higher voltages numerous corona discharges were occurring at several spots where sharp edges were exposed, providing parallel current paths and thus giving misleading data. In an attempt to remedy this situation, all leads were brought into two spherical brass junctions. Wherever any sharp edges were present an attempt was made to round them off. The I-V data then taken are shown in Figure VI. For a detailed report on the operation of the unit as a generator (with collector current data) and effectiveness of design innovations refer to reference 6.

III. COLLOIDAL ION SOURCE

A. INTRODUCTION

The second phase of this study entails the major part of the research carried out in the preparation of this thesis. This phase is concerned with devising a means of injection of ions of a much greater size than ionized air into the air flow downstream from the cylinder.

An important consideration in the design of an effective EGD generator is the mobility of the charged particles which are to be forced out to the collector. Mobility is a measure of the velocity of a charged particle under the influence of an electric field. A high mobility indicates that it would be difficult to force the ions away from their migration path from the needle tip to the ring and therefore a low mobility is desirable. In a study[4] carried out for the Aerospace Research Laboratories published in 1964, it was reported that particle size is an important factor governing the mobility of the ions. As shown below, particles on the order of 10^{-7} meters to 10^{-6} meters (one micron) in diameter provide a somewhat optimal mobility for EGD considerations.

A comparison between the usefulness of molecular ions and larger sized ions can be made using the mobility calculations of reference 4. Consider the drift velocity of an ion charged in a corona device under an electric field of 3.0×10^{6} volts/m (breakdown potential (E_b) of air at STP). The respective drift velocities (v_D) are given below.

molecular ion: mobility (μ) $\cong 10^{-4}$ m^2/volt-sec

$$v_D = \mu E_b \cong 3.0 \times 10^2 \text{ m/sec} \cong 9.84 \times 10^2 \text{ ft/sec}$$

micron sized ion: $\mu \cong 10^{-6}$ m^2/volt-sec

$$v_D = \mu E_b \cong 3.0 \text{ m/sec} \cong 9.84 \text{ ft/sec}$$

As can be seen, the molecular ions can easily attain drift speeds greater than that of the main flow and little interception can be expected; whereas the micron sized ions drift relatively slowly and can be intercepted more readily by the flow. The situation improves further with particle sizes between 10^{-8} and 10^{-7} meters.

Having determined the desired size for the charged particles, and acting on the decision to retain the corona as a source of ion generation, it was then necessary to choose a means of producing charged particles which would be of the order of one micron in diameter. Three methods of producing micron-size particles were considered and are described below. The method employing saturated steam was chosen.

Method one involved the use of powder which is manufactured to have an average particle size of one micron. The powder could then be introduced to the air flow upstream of the cylinder and channeled through the corona unit. This is perhaps the simplest method and guarantees the proper particle size, but it does have the disadvantages of both the necessity of a large supply of powder and the discomfort of exhaust powder from the open system, which could provide a hazard to metering operation as well. Furthermore, it is difficult to produce homogeneous charged particle distributions.

The second method considered was to replace the needle tip of the corona with a hypodermic needle.[5] In this way a dielectric fluid could be forced out through the needle at a controlled rate. As droplets of dielectric form at the needle tip, the high electric field strength charges them and subsequently causes them to break up. Unfortunately, there is no good way with this method to insure proper particle size.[9]

Finally, a method has been studied whereby saturated steam is condensed by means of expansion through a nozzle.[2] The dry steam would

initially be forced through a corona unit as close as possible to the point of condensation. Then, in theory, the steam would saturate and condense about the ions, forming a colloidal suspension of charged water droplets in air. The steam is employed both as the dielectric and as the carrier gas to force the ions out of the nozzle. This method was chosen as the best suited for the work which has been done here although, admittedly, it also presents the problem of how to grow the proper ion size during condensation.

B. DESIGN OF COLLOIDAL ION GENERATOR

A design was sought which would incorporate the cylinder with a steam supply, a nozzle and a corona device. The design chosen involved a hollow teflon cylinder fitted with a stainless steel nozzle which would face the downstream direction of the flow. In this configuration the nozzle could serve a three fold purpose. It would act as a flow metering device, yielding any desired flow rate based on a supply of saturated steam (i.e., 250°F. and 15 psig). Additionally, it would serve as the ring of the corona unit and finally serve to condense the steam about the charged ions through expansion at the nozzle exit plane. A diagram of the nozzle and cylinder is shown in Figure VII. Sample calculations and principles for nozzle design are shown in the Appendixes. Three nozzles were constructed to have steam flow rates of .01 lbm/sec, .005 lbm/sec and .001 lbm/sec, all with a choked steam flow at the exit plane.

In order to have a generator capable of producing a constant supply of steam at the desired temperature and pressure it was decided that a sealed and reinforced aluminum container would be the most desirable. A pressure cooker served nicely for this purpose. The generated steam

would then be transported to the cylinder and nozzle by means of ¼-inch O.D. stainless tubing. A ball valve was placed into this line to serve as an on-off valve. Any excess pressure would be bled off by means of a needle valve installed on a length of tubing which led away from the main line. The total length of tubing from the pressure cooker to the cylinder was wrapped in heating tape to prevent condensation of the steam while it was in the line (see Figures VIII-IX). A pressure gauge was installed in the top of the cooker in order to provide a guide for pressure regulation.

Initial testing of this new unit was solely concerned with perfecting as much as possible the steam generation aspect of the system. A 4000 watt hot plate was found, which easily maintained a 15 psig pressure head. After completely insulating the top and sides of the pressure cooker with a layer of Sauereisen number 31 cement of approximately ½-inch in thickness and then another ¼-inch thick layer of asbestos tape, condensation problems were solved well enough to maintain a steady flow of dry steam through the nozzle and thereby prevent any arcing of the corona due to spurts of condensed water. A length of twenty-thousandths-inch platinum wire was brought in from the upstream side of the cylinder and centered within the nozzle to serve as the needle tip of the corona unit (see Figure VII).

C. EXPERIMENTAL PROCEDURE

As previously mentioned, before any reliable electric data could be obtained, it was necessary to insure that a steady and dry steam flow would be emitted from the nozzle. To achieve this end the steam line was purged with a jet of high pressure air prior to each test. When this was accomplished the ball valve which separated the nozzle from the

pressure cooker was closed to seal off any steam flow in that direction. The four-quart pressure cooker was then filled to approximately three quarters of its capacity with distilled water and the hot plate was turned on to the maximum heating position.

It took about twenty minutes for the water to begin to boil. During this interim the heating tape, which was connected on line with a rheostat, was maintained at 400°F. to ensure that the inner tubing temperature would be greater than the temperature of the steam and thus aid in preventing any condensation in the line.

Initial data taking involved a set of I-V curves on the nozzle and needle as a corona unit. During these tests there was no steam flow through the nozzle. A set of these data is shown in Figure X. These tests were usually carried out during the period when the distilled water in the pressure cooker was being raised to the boiling point.

As soon as the water began to boil at a substantial rate all valves were closed until the internal pressure in the pressure cooker reached 15 psig. When this point was reached the bleed off needle valve was opened just enough to maintain this pressure. This action was continued for several minutes in order to insure that the water had reached its boiling point at the higher pressure. The ball valve was then opened to allow the steam flow to go up the line and through the nozzle as the needle valve was readjusted in order to steady the internal pressure at a constant 15 psig. It was also necessary to increase the rheostat setting, since the steam flow had a considerable cooling effect on the tubing. A heating tape temperature of about 350°F. (measured by a thermocouple mounted between the tape and the tubing) was found to be sufficient to avoid condensation.

When a steady steam flow was obtained I-V data were again taken on the corona within the nozzle. These data are shown in Figure XI. Electrical connections and metering setups are shown in Figure XII. At this point all systems were ready for a test of the unit as a generator (see Figures XIII, XIV and XV).

An iron nail, polished and sharpened, was insulated by plexiglass and mounted on a traversal mechanism. The tip of the nail served as the collector unit. It was wired to a microammeter and then to ground. Tests were then run measuring the corona voltage, corona current and collector current for both polarities on the corona. The collector position downstream of the nozzle was a variable as was the corona voltage. These tests were run at first using only the steam flow to force the charged particles out to the collector. A later test was made to determine the effect of the air flow in conjunction with the colloidal ion injection. Data are presented on Figures XVI, XVII and XVIII. Results and the effectiveness of system modifications are discussed in the Analysis of Results section of this paper.

IV. ANALYSIS OF RESULTS

The first test of the complete system proved rather discouraging as there was no measurable current flow from the collector. Two modifications in the system were simultaneously devised. A digital multimeter, capable of measuring down to one hundredth of a microampere, replaced the Simpson microammeter (see Figure XV). Secondly, it was deemed that with the configuration of the ion generator it would be advantageous to devise a means of aiding the process of getting the colloidal ions out into the region of the collector. As a solution of this problem the interior of the nozzle was coated with a thin layer of dielectric epoxy, with only a narrow band of steel at the throat of the nozzle left exposed, (see (Figure XIX). With the tip of the center needle recessed back into the nozzle, this would then align the direction of the electric force field toward the nozzle throat. Finally, to prevent the collector from acting as a discharge point when placed too near to the nozzle, a set of diodes was connected in series between the collector and the multimeter. With these improvements a measurable, though admittedly small, collector current was drawn, (see Figures XVI, XVII, and XVIII).

Three primary observations were made from the data thus obtained. First of these is that the ion density was primarily a function of streamwise distance from the nozzle exit plane. Positioning of the collector in various points off center of this axis had little effect on the current reading. Secondly, the collector current reading for the negative ion case was about double that for the positive ion case. Though consistent with the results of other researchers,[2] the reason

for this phenomenon remains to be uncovered. Thirdly, colloidal ion suspensions were shown to be considerably more effective in the generator operation than higher mobility air ions.[6]

The epoxy coating on the inside of the nozzle was helpful, but it was a crude solution at best. The ineffect of corona voltage increase on collector current may indicate a breakdown of the dielectric epoxy in this region. This hypothesis is based on the observation that at lower voltages on one test a significant self induced oscillation of corona current produced a proportional oscillation of collector current, (see Figure XVII). While on the same run at higher corona voltages and therefore increased corona current, the collector current was essentially constant, (see Figure XVIII). These higher voltage currents were far more stable than lower readings, but the point to be observed here is that the increased current did not proportionally increase the collector current as it had at lower voltage values.

Results given on this study are all for the nozzle designed to yield a flow rate of 0.001 lbm/sec. Use of the larger nozzles was attempted, but the present steam generator was not capable of maintaining a pressure head at these nozzles. A heating method with a greater BTU capacity and improved insulation would be required to overcome this hurdle.

The addition of air flow through the test section detracted from rather than aided the performance of the system. Admittedly little work was done with this configuration in air flow due to the time spent in perfecting the steam generator and achieving a non-air flow collector current. It is very possible that the injector design simply works better by relying only on steam for a carrier gas and expansion for condensation. It may also be that there is an air flow rate which would be favorable to the process. This study has yet to be carried out.

The data presented here must be interpereted taking into account the fact that the existence of micron sized particles was not proven by this study. Further, if they did exist, no attempt has been made to determine at what point in the flow they were condensed.

Finally, no leakage of current between the injector and the collector was anticipated. Therefore, no test of the generator unit was made without steam or air flow. The possibility of this leakage should, however, be considered in an analysis of this data.

V. CONCLUSIONS

The injector designs which were sought at the start of this project were built and successfully operated. A discussion of efficiency by usual standards at this point would be rather premature due to the somewhat limited state of development of the hardware. Positive, though not conclusive, results were obtained. It is hoped that these results prove helpful to future studies.

VI. RECOMMENDATIONS

The design of the colloidal ion generator should be reviewed. It would seem advisable to design a system which would employ the air flow to carry the colloidal ions out of the corona region, rather than rely so heavily on the steam flow. The use of the nozzle should be maintained, but an improved system should include a way to feed flowing air into the nozzle entrance plane without prematurely condensing the steam.

The system which has been used in this research could also be improved upon enough to bring about a marked increase in collector current. The first improvement needed here is to get a smooth dielectric coating on the inside of the nozzle, such as a thin teflon cone. This will lessen the doubts raised concerning the breakdown of the rough epoxy coating used in this work. Secondly, an increased steam flow rate would be greatly helpful in getting the colloidal ions out to where they can be gathered by the collector. The nozzles for this purpose have already been built. All that remains to be done is to generate steam fast enough to maintain the desired pressure head. Finally, a study with air flow should be made to determine the compatibility of this present system with original design criterion.

It is also noted here that there has been no attempt made as yet to determine at what distance from the nozzle exit plane the micron sized ions are condensed, if they existed at all. Several studies have been made of the rates of condensation which may prove useful to an investigation of this aspect of the EGD generator. Two of these are listed in the bibliography for future reference[10,11].

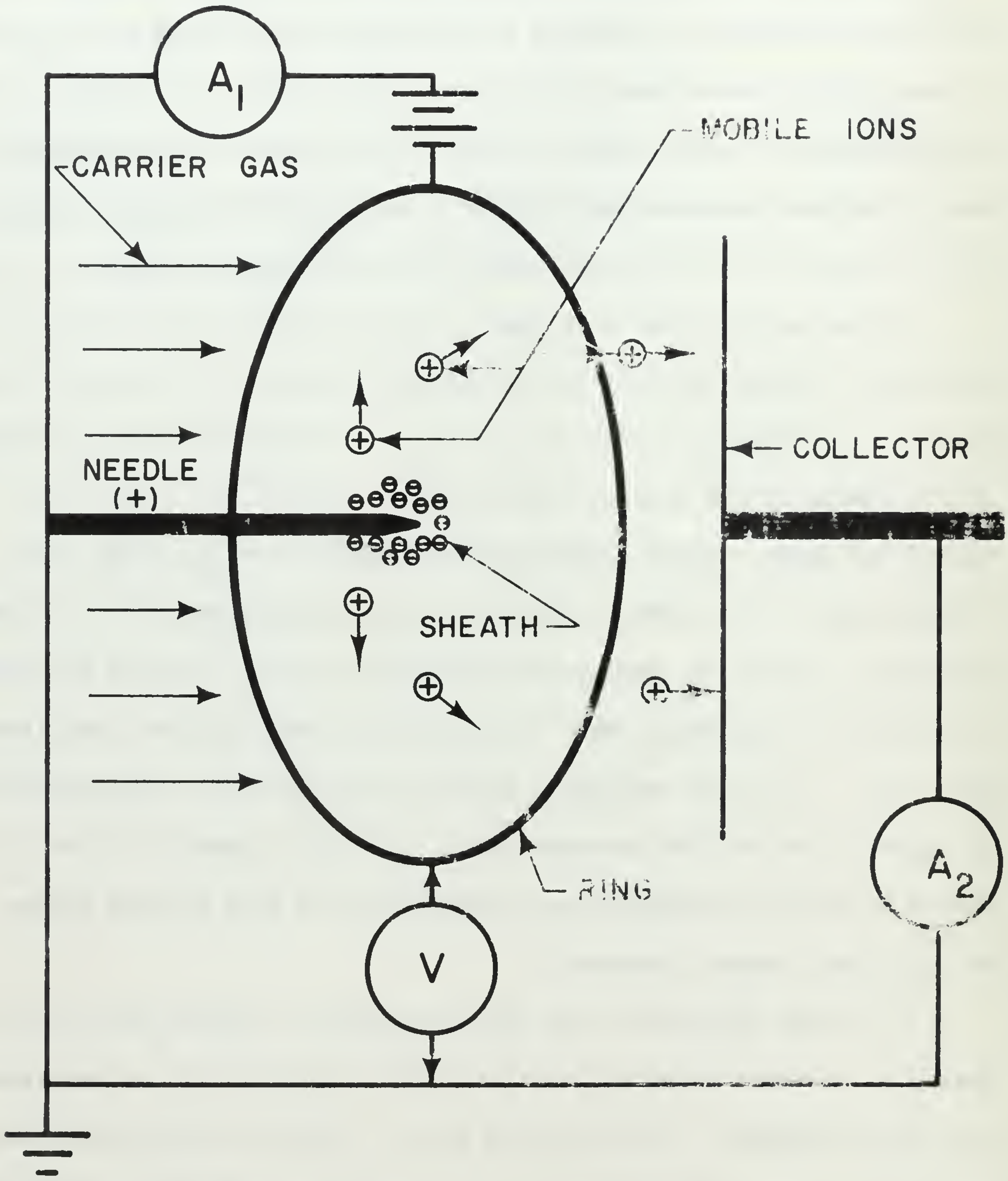


FIGURE I GENERATOR SCHEMATIC

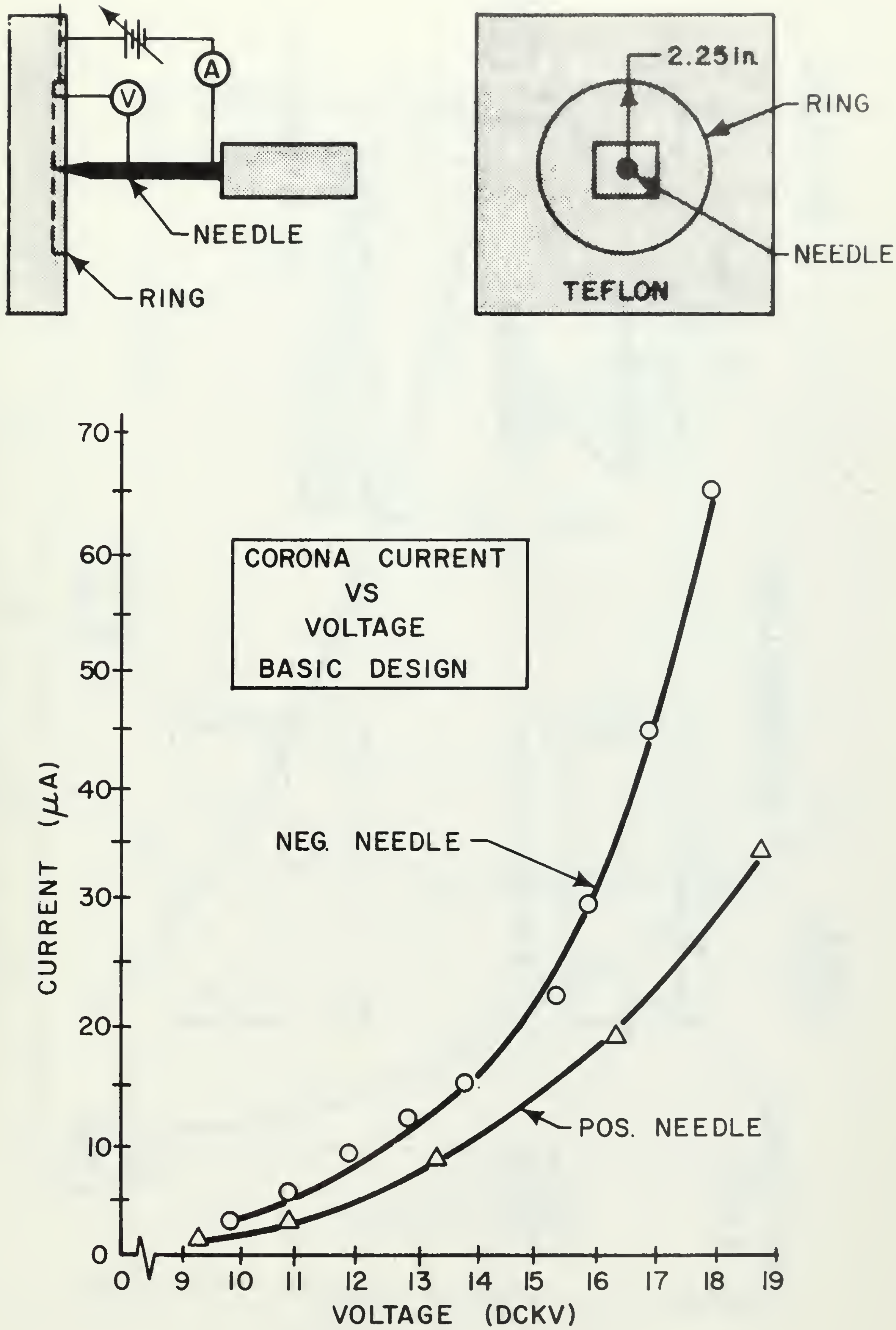


FIGURE II PRELIMINARY CORONA DEVICE

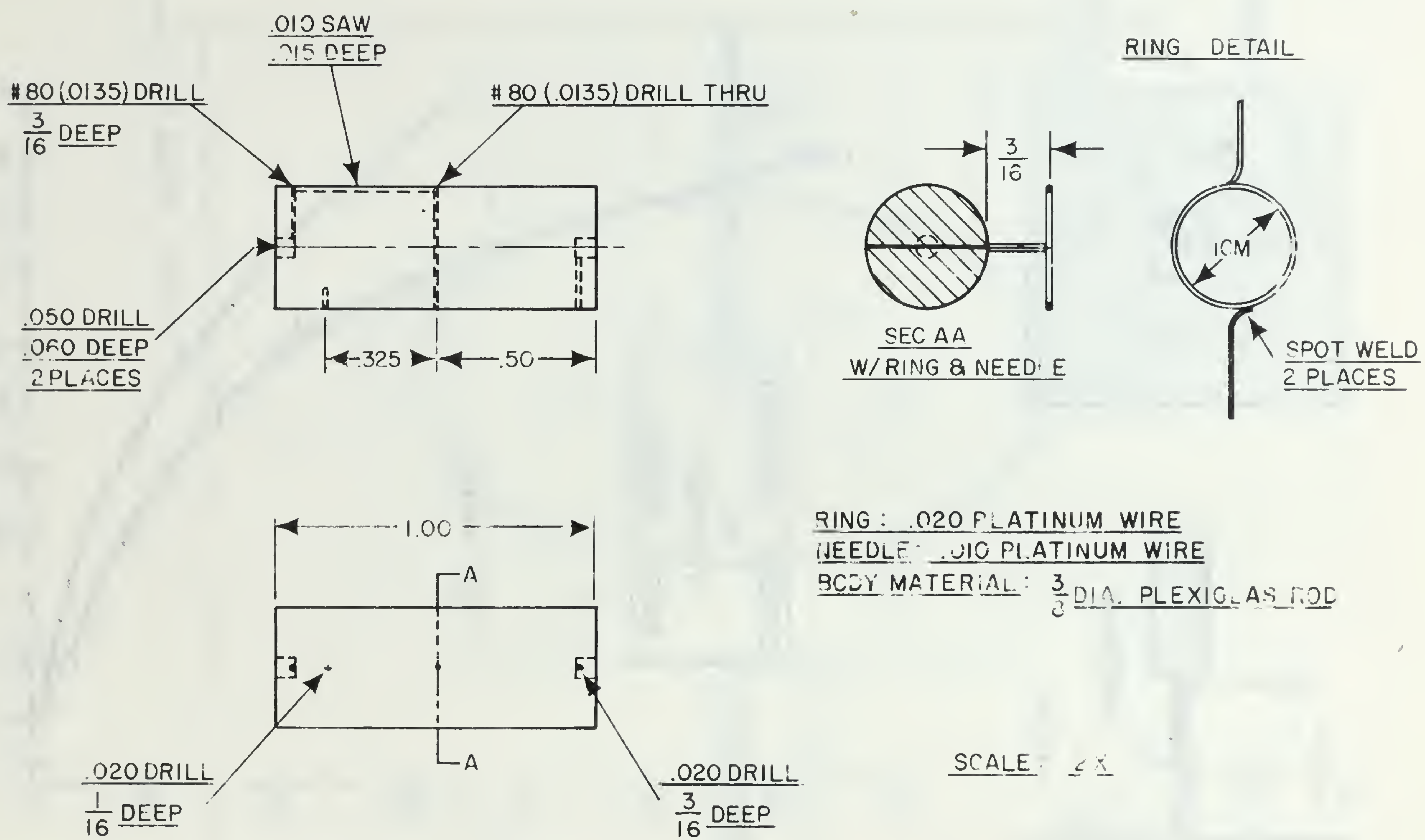


FIGURE III MOLECULAR ION DEVICE

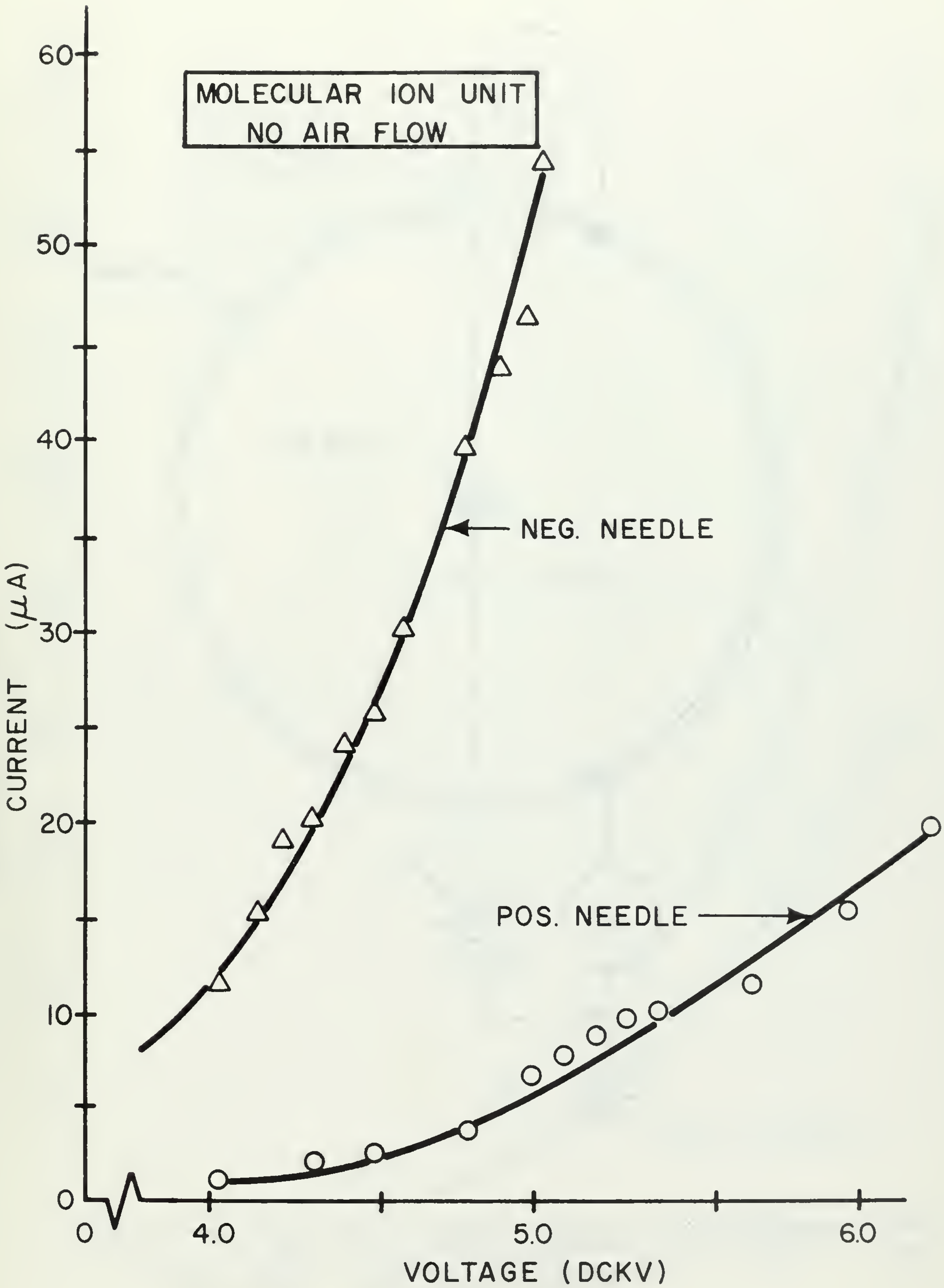


FIGURE IV CORONA CURRENT VS VOLTAGE
MOLECULAR ION UNIT

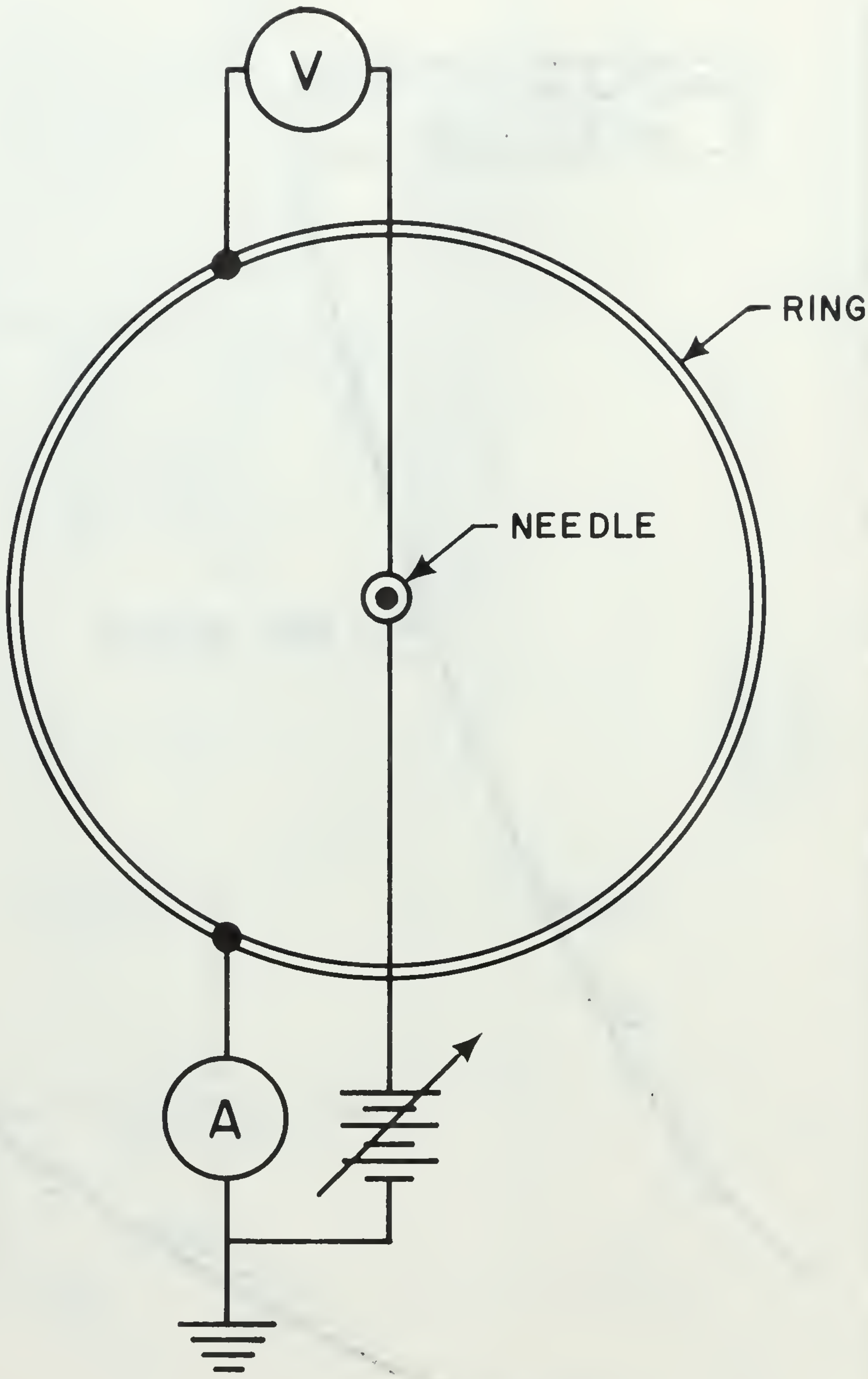


FIGURE V ELECTRICAL SETUP OF MOLECULAR ION INJECTOR

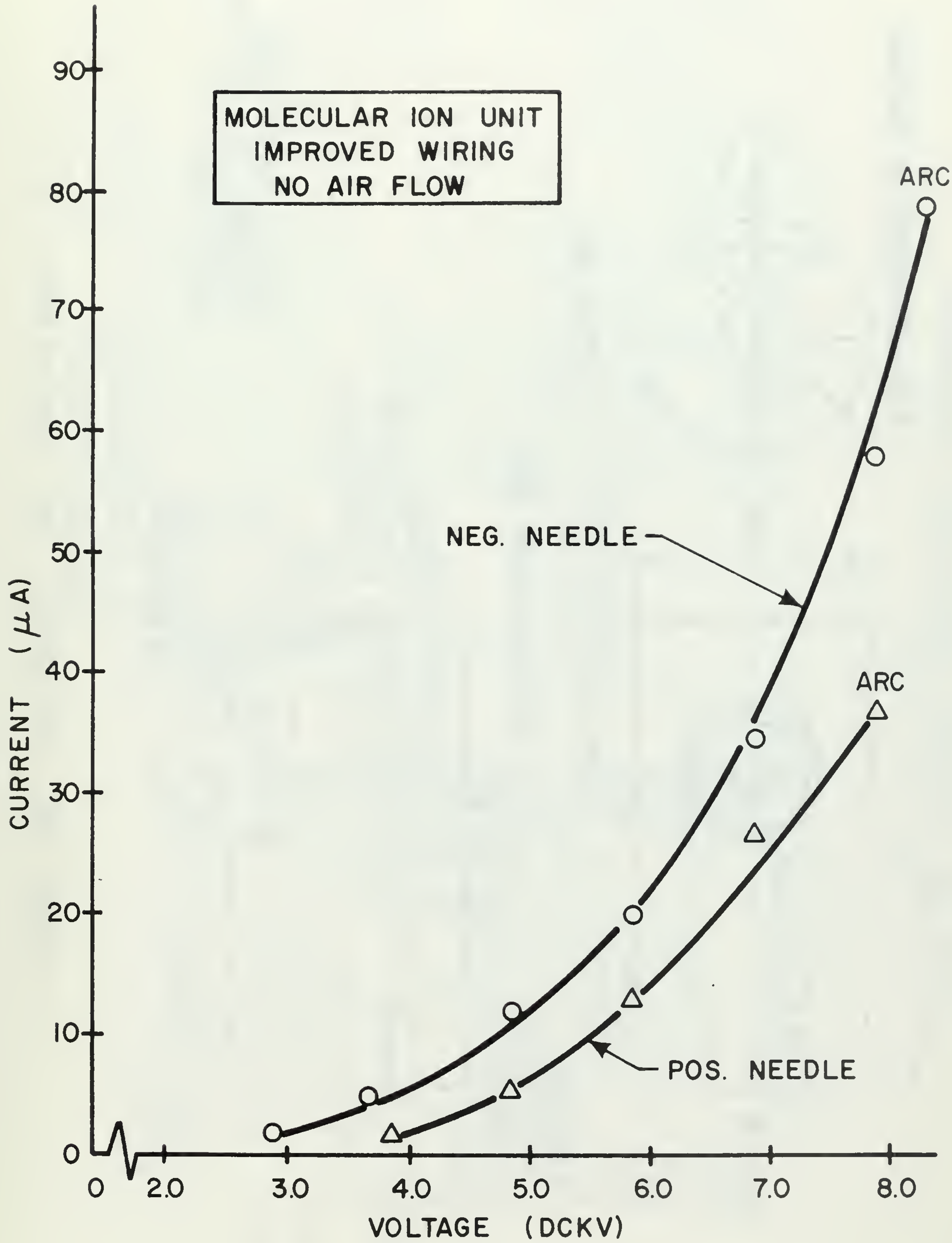


FIGURE VI CORONA CURRENT VS VOLTAGE
MOLECULAR ION UNIT

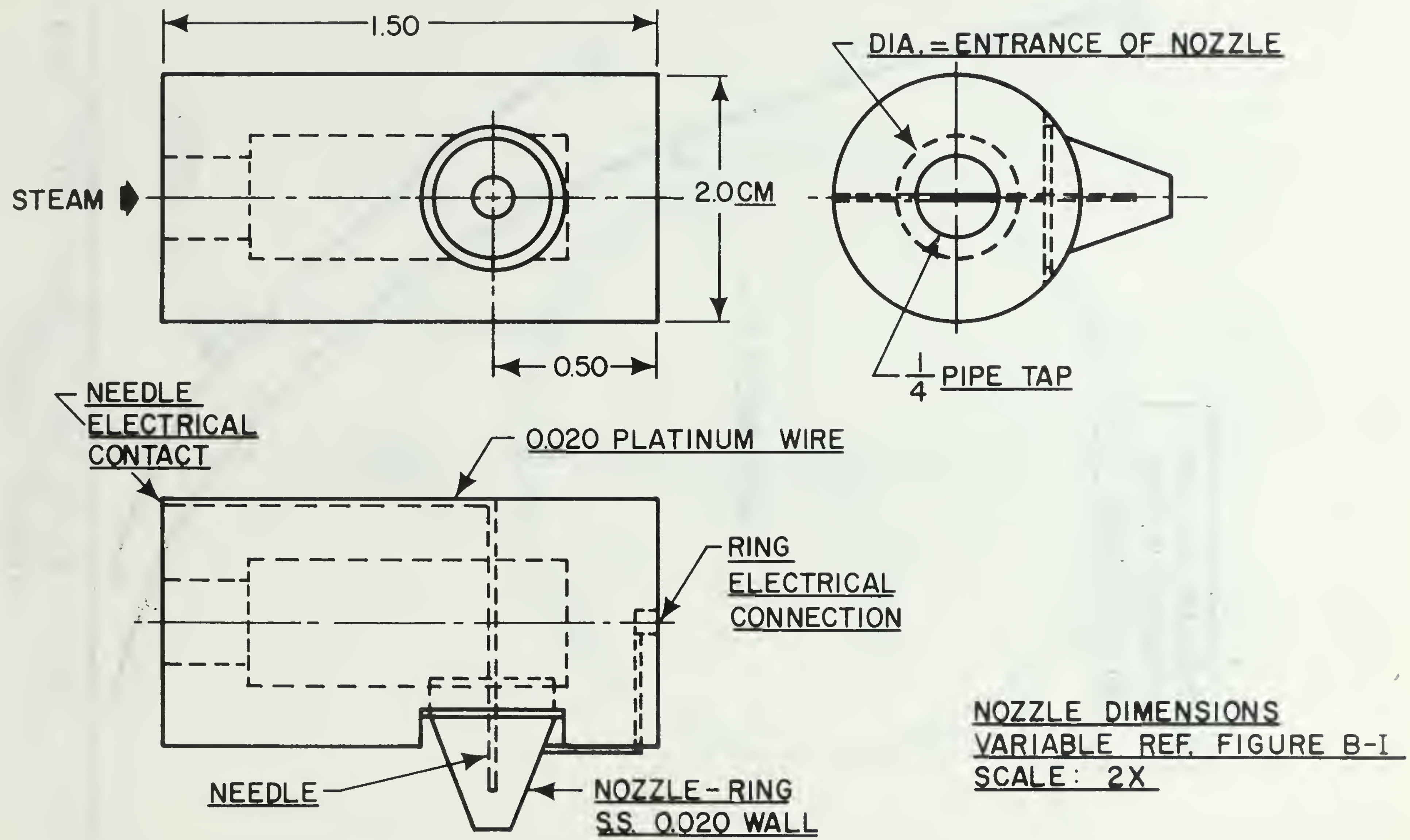


FIGURE VII COLLOIDAL ION GENERATOR

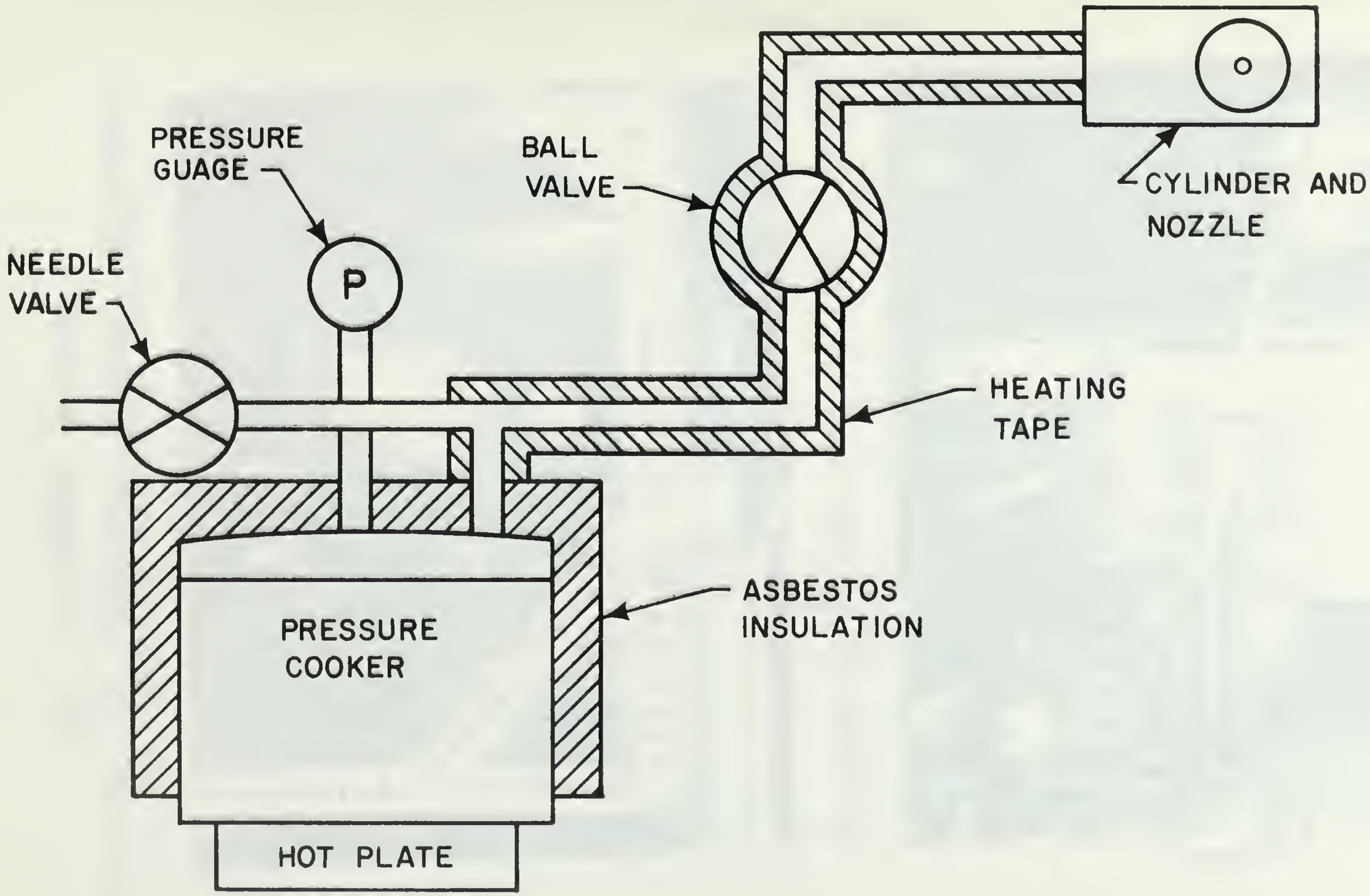
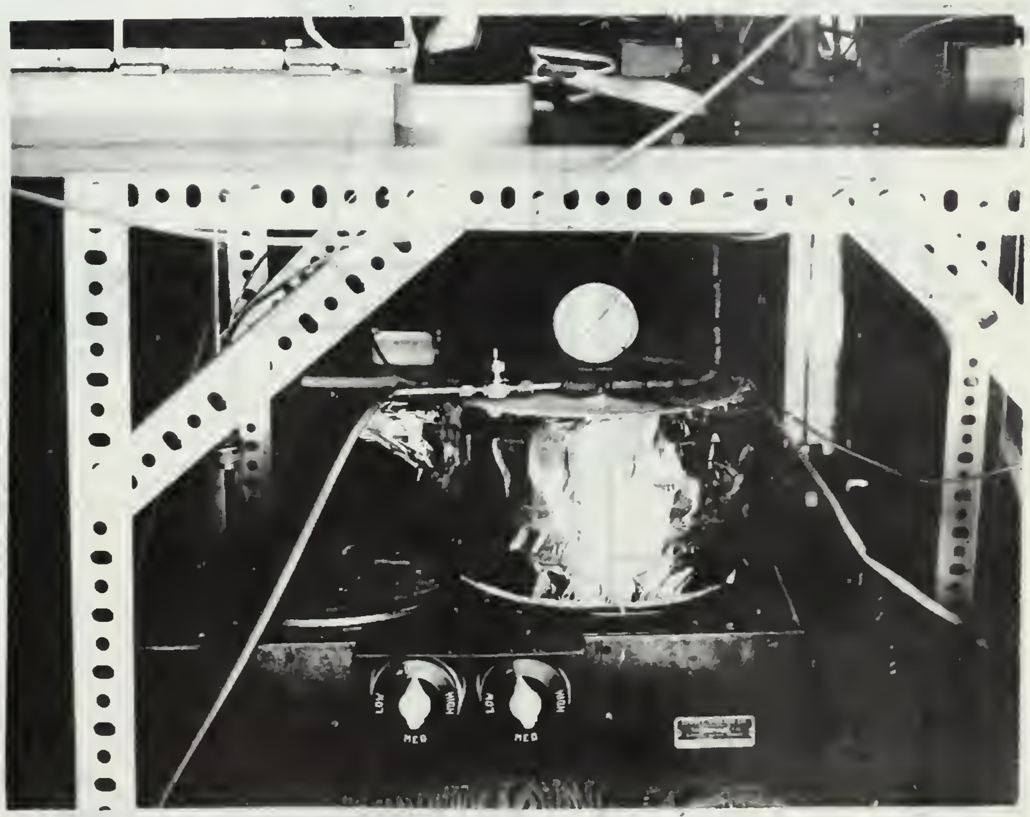


FIGURE VIII STEAM GENERATOR SCHEMATIC

(i) VIEW OF STEAM UNIT IN TEST CHANNEL



(ii) VIEW OF PRESSURE COOKER

FIGURE IX

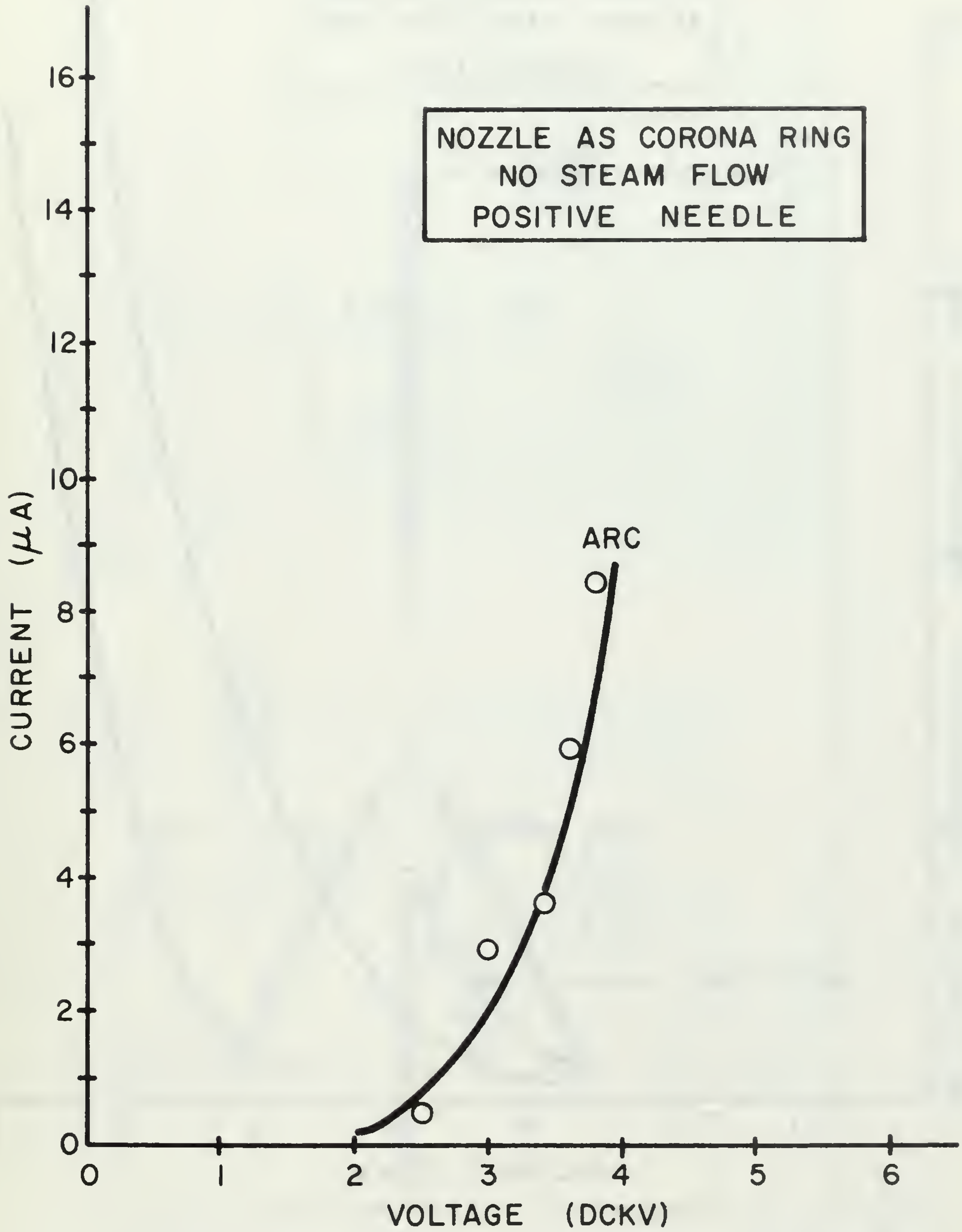


FIGURE X CORONA CURRENT VS VOLTAGE
MICRON INJECTOR UNIT

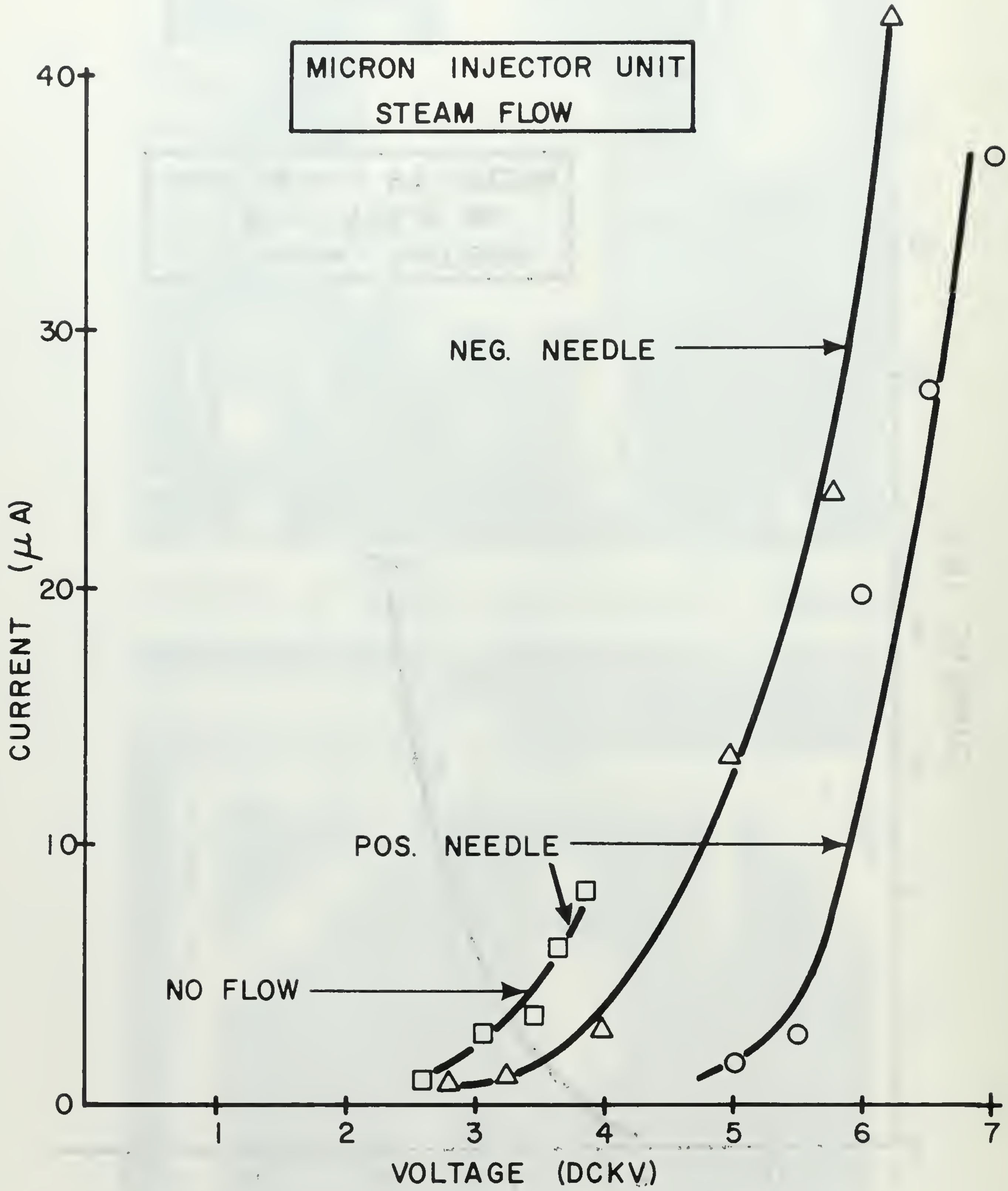


FIGURE XI CORONA CURRENT VS VOLTAGE
MICRON INJECTOR UNIT

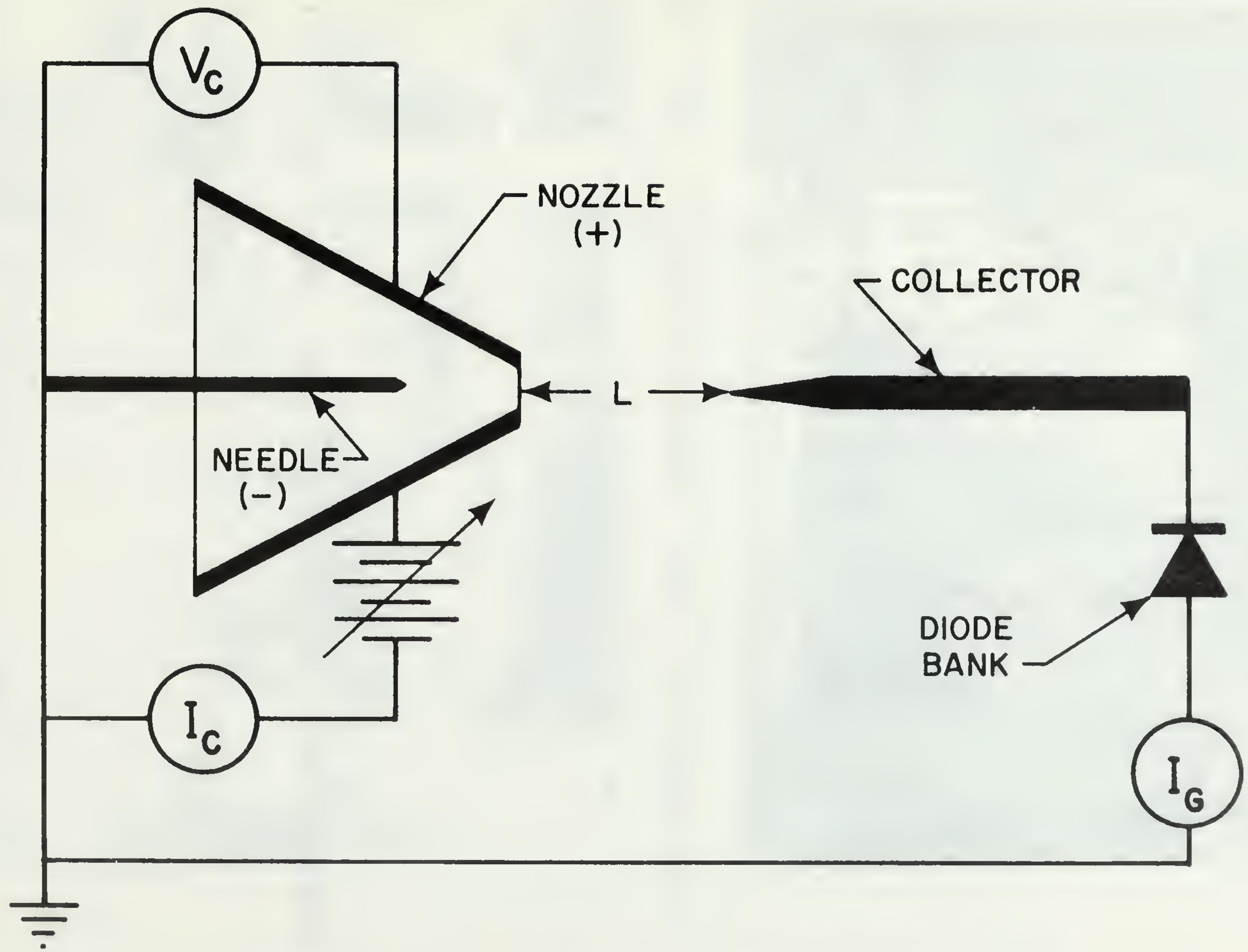


FIGURE XII ELECTRICAL SCHEMATIC OF MICRON INJECTOR UNIT

FIGURE XIII GENERATOR UNIT IN TEST SECTION

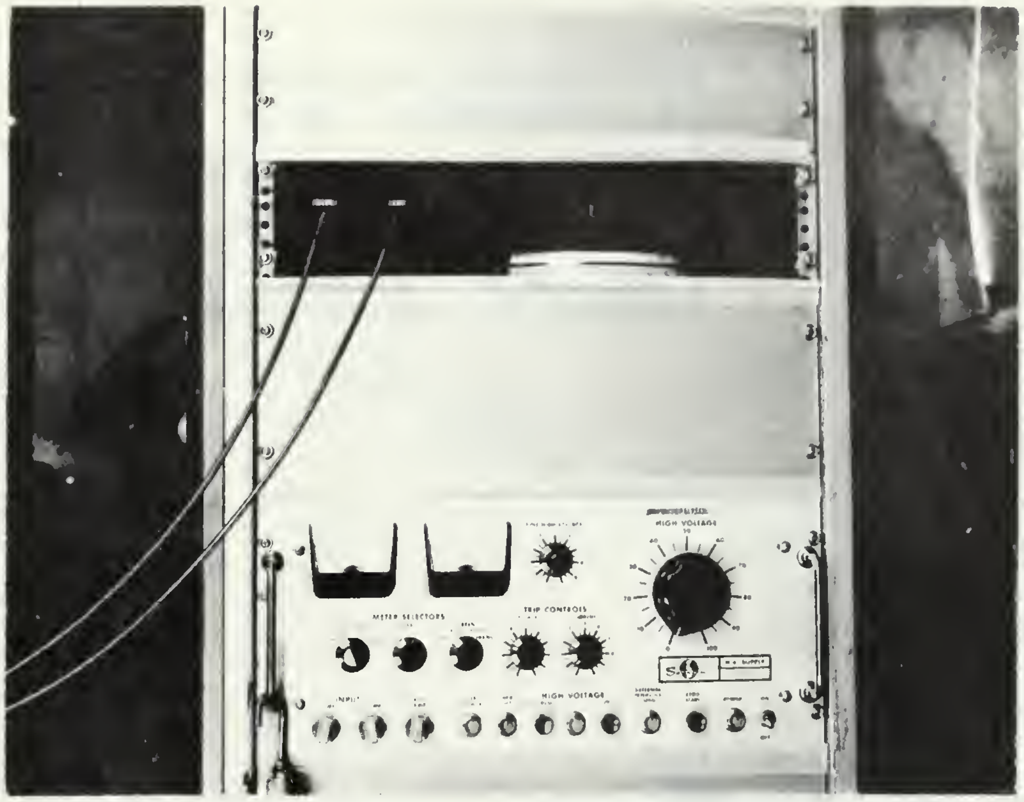


FIGURE XIV POWER SOURCE AND VOLTMETER

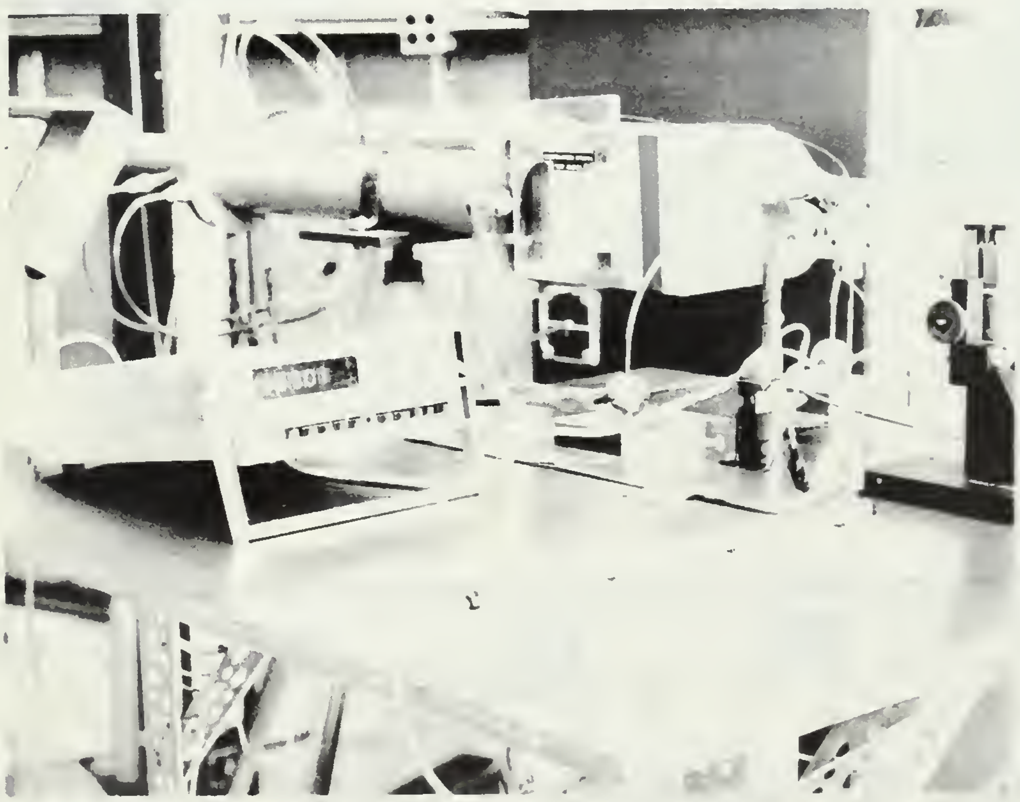


FIGURE XV MULTIMETER AND DIODE BANK

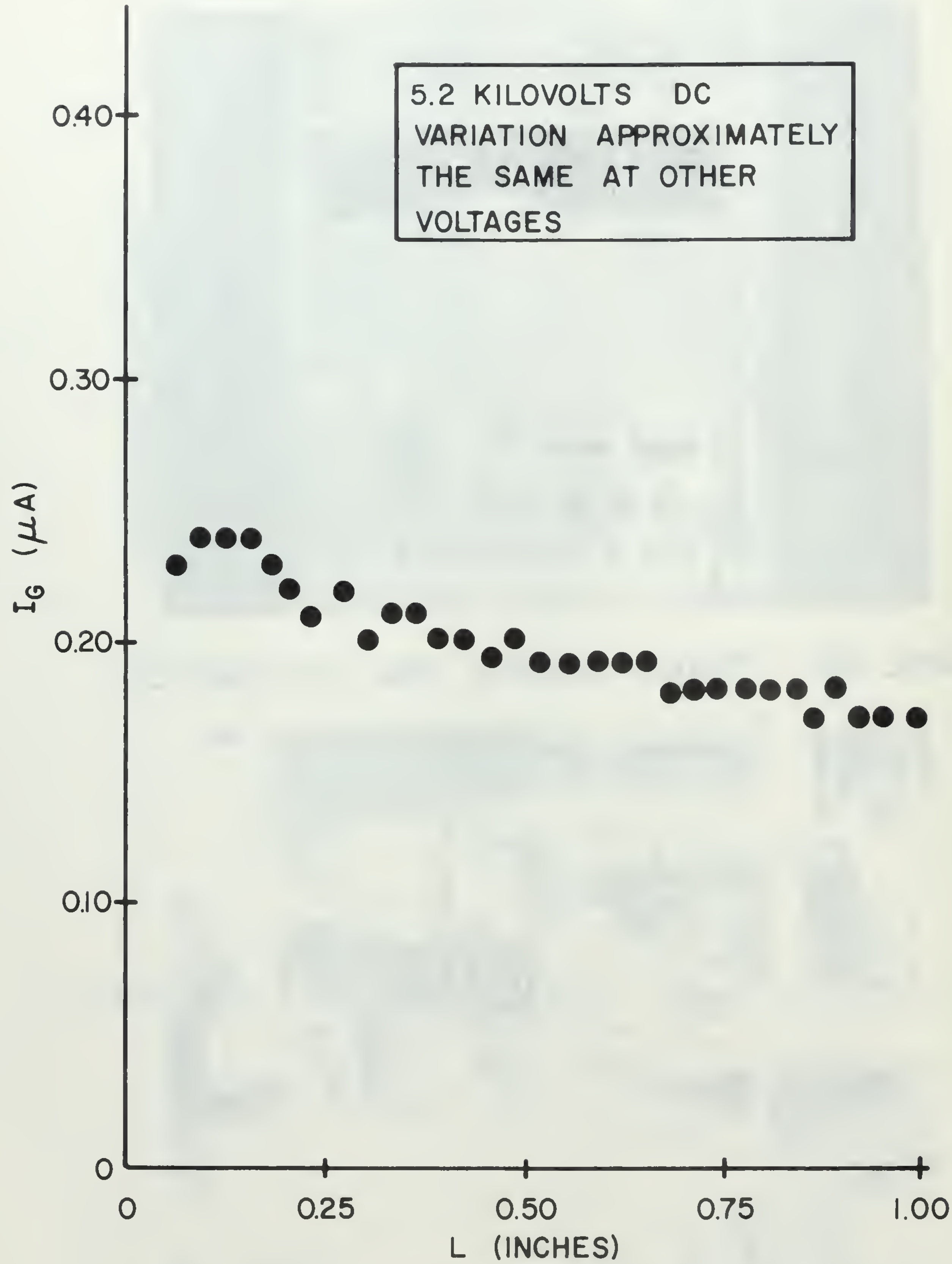


FIGURE XVI GENERATOR CURRENT VS COLLECTOR DISTANCE FROM NOZZLE EXIT

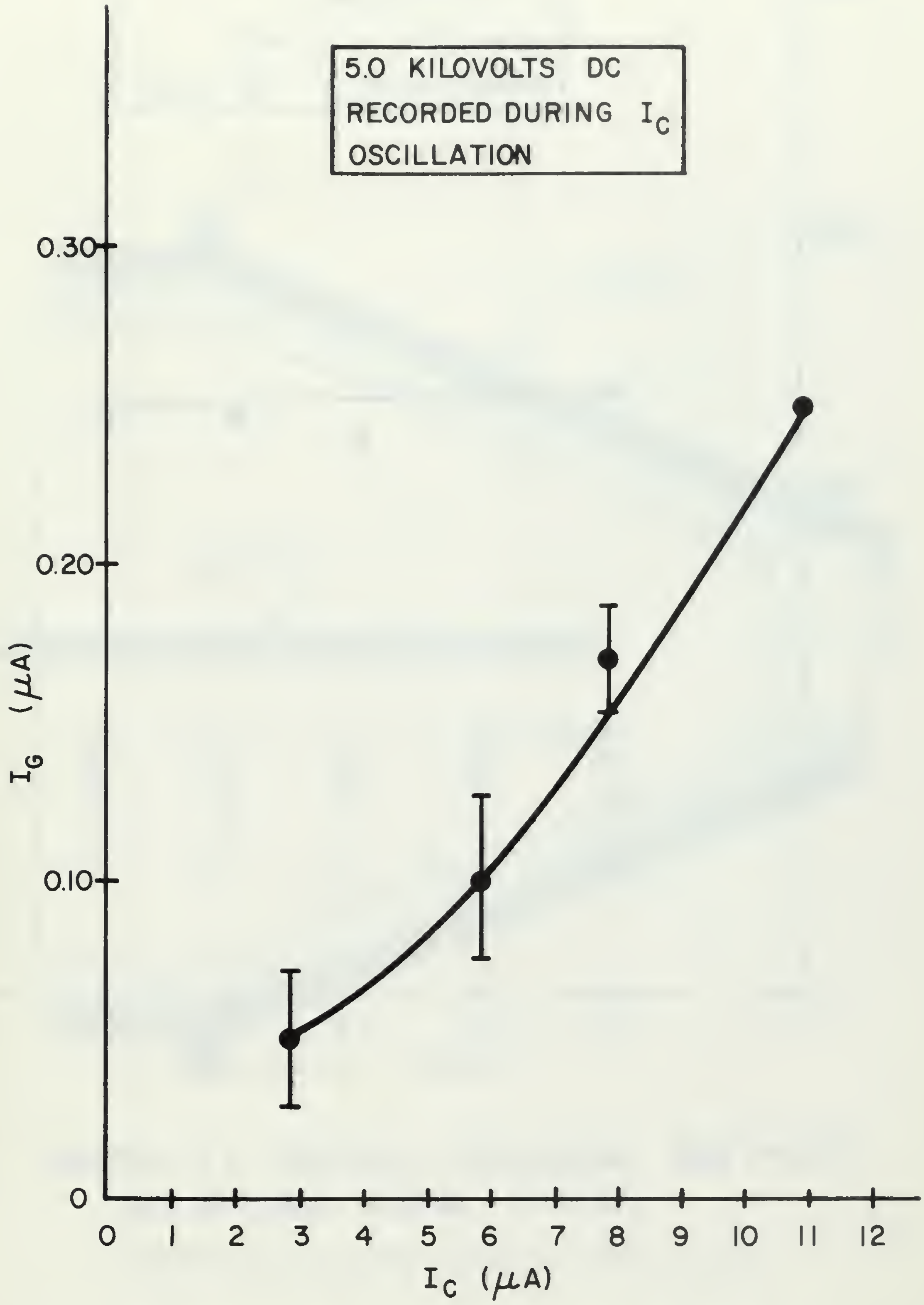


FIGURE XVII GENERATOR CURRENT VS CORONA CURRENT - MICRON INJECTOR UNIT

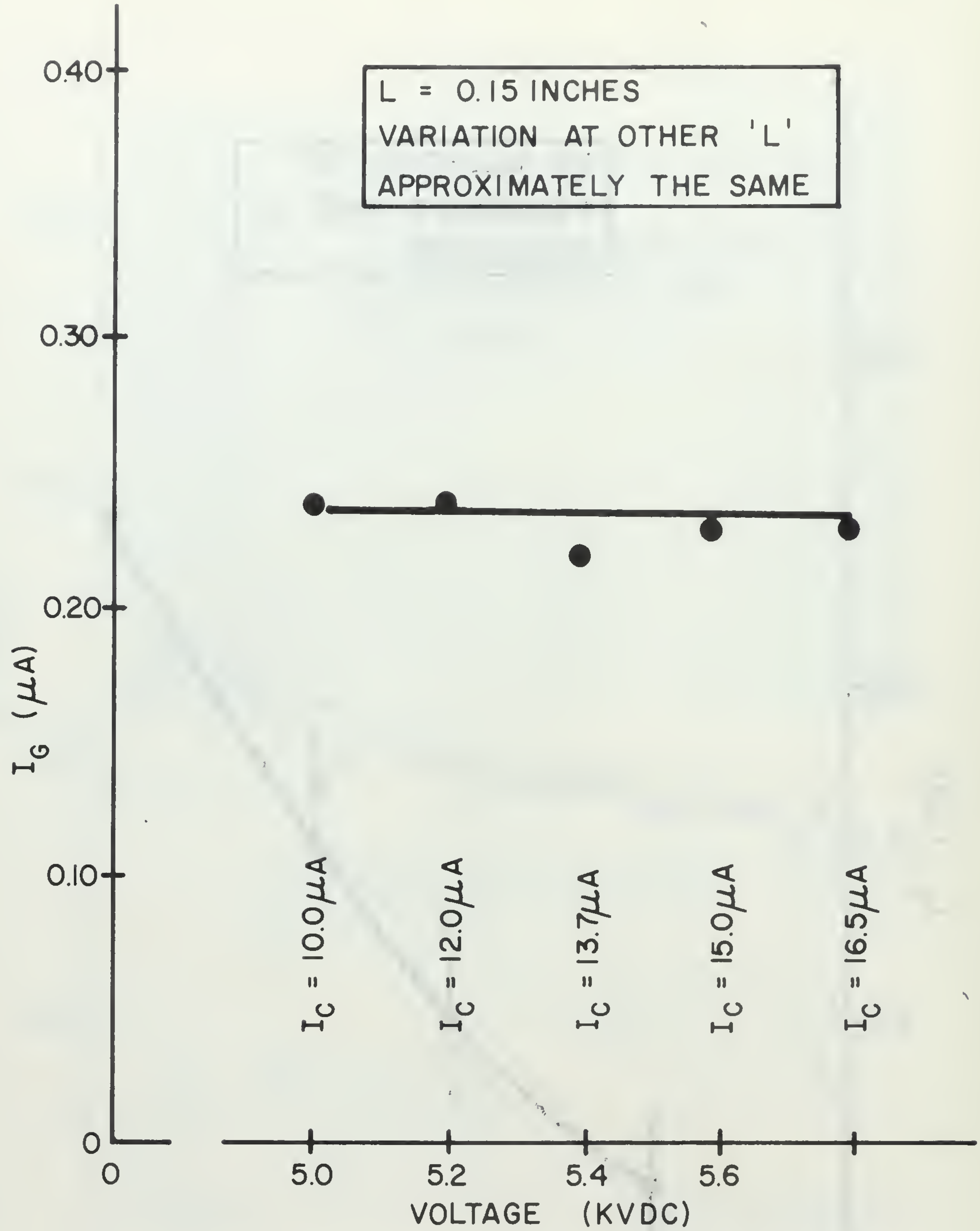


FIGURE XVIII GENERATOR CURRENT VS CORONA VOLTAGE - MICRON INJECTOR UNIT

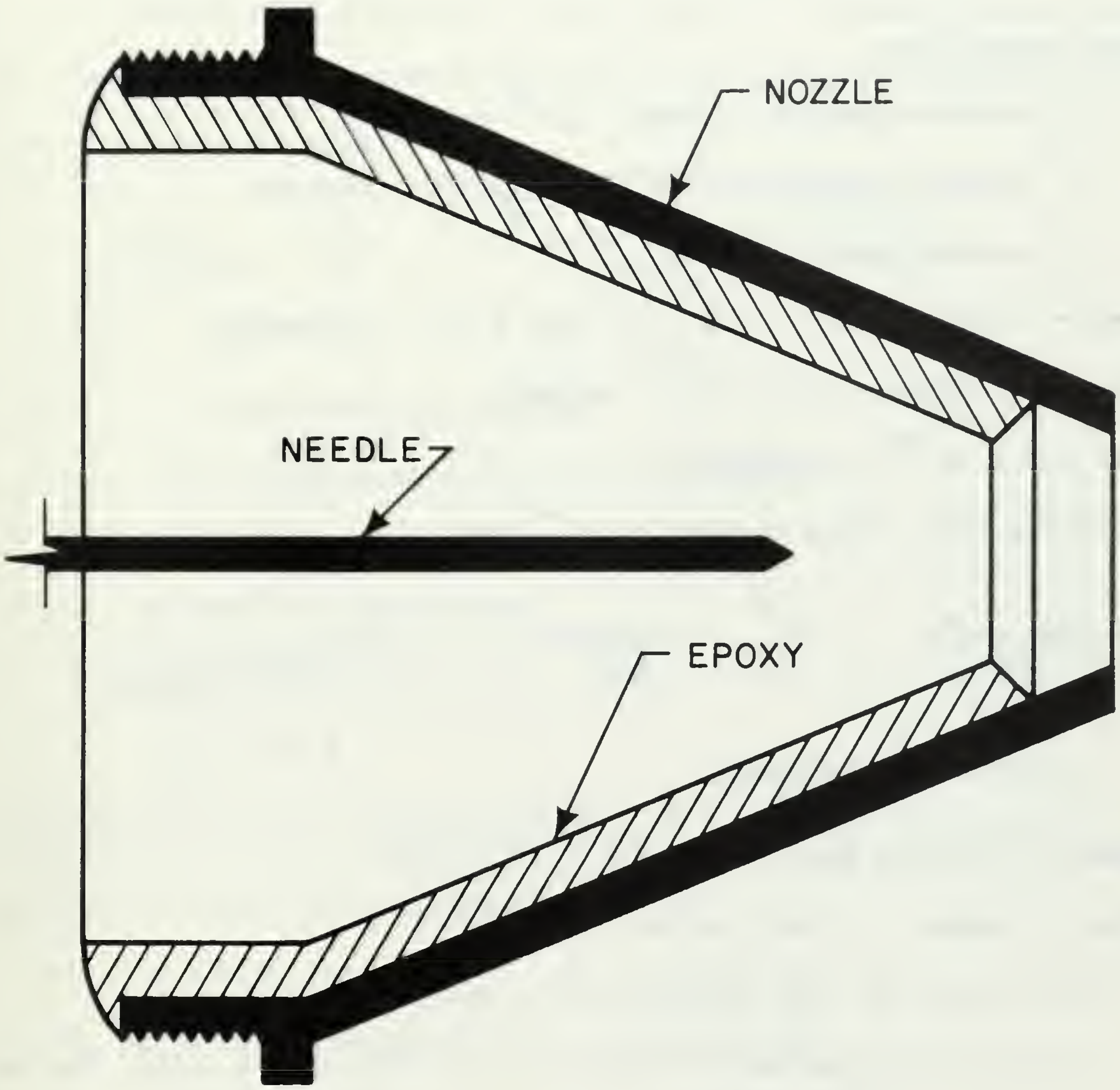


FIGURE XIX EPOXY COATING ON NOZZLE

APPENDIX A

CALCULATION OF NECESSARY STEAM

FLOW RATE

Basic assumptions:

1. maximum desired current = 10^{-4} amperes
2. average charge per ion = 10^{2} electron charges
3. micron sized ions

1 amp = 1 coulomb/sec $\quad \therefore \quad 10^{-4}$ amp = 10^{-4} coulomb/sec

1 electron charge = 1.6×10^{-19} coulomb

$\therefore$ 1.6×10^{-17} coulomb/ion

It follows that, for a current of 10^{-4} amp:

$$\frac{\text{ions req'd}}{\text{sec}} = 10^{-4} \frac{\text{coulomb}}{\text{sec}} \times \frac{\text{ion}}{1.6 \times 10^{-17} \text{ coulomb}}$$

$$= 6.25 \times 10^{12} \text{ ions/sec}$$

Volume of 1 micron particle = 5.25×10^{-13} cm^3

Density of water = 2.204 lbm/cm^3 (liquid)

$\therefore$ Flow rate for 100% charging efficiency =

6.25×10^{12} ions/sec X 5.25×10^{-13} cm^3/ion X 2.2×10^{-3} lbm/cm

= 7.25×10^{-3} lbm/sec

With this flow rate as a basis, steam mass flow rates were chosen which would bracket the theoretical value.

APPENDIX B

CALCULATION OF NOZZLE EXIT AREAS

Assumption:

1. Superheated steam may be approximately treated as an ideal gas. The analysis below represents a preliminary estimate of the exit areas. Ideal gas equation used[8]:

$$\left(\frac{W}{A}\right)_{max} = \frac{W}{A^*} = \sqrt{\frac{k}{R}\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}}\ \frac{P_o}{\sqrt{T_o}}$$

where:

W = mass flow rate lbm/sec

A^* = nozzle exit area for choked flow

$k = c_p/c_v$ for steam = 1.33

R = 85.6 ft-lbf/ R-lbm

P_o = 30 psi

T_o = 710° R

Substituting into the above equation, the following exit areas were obtained for each selected flow rate:

1. W = 0.01 lbm/sec, A = 0.02157 in^2
2. W = 0.005 lbm/sec, A = 0.01079 in^2
3. W = 0.001 lbm/sec, A = 0.002157 in^2

Nozzles were designed with the following guidelines:

1. Add 10% to exit area for real gas effects
2. Nozzle half angle to be approx. 30°.
3. Max nozzle length to be approx. 1 cm.
4. Max entrance to exit area ratio = 20.

The nozzle dimensions are shown in Figure B-1. No attempt has been made as yet to determine what the actual flow rate for each nozzle is.

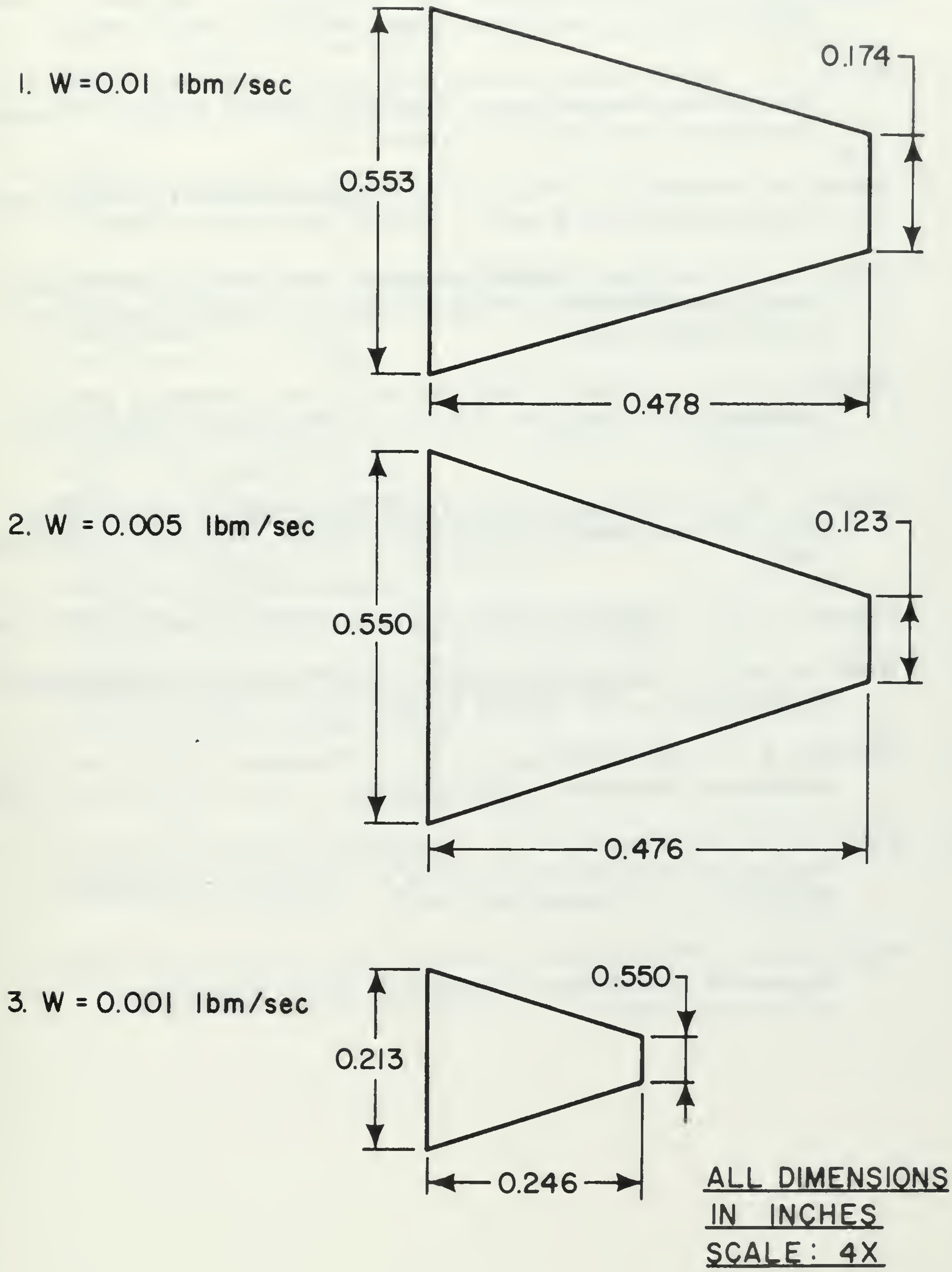


FIGURE B-I NOZZLE DIMENSIONS

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13. ABSTRACT

Systems suitable for the injection of ions into electrogasdynamic (EGD) generator devices were built and tested. The mechanism of injection was based on a corona discharge, whereby ions moving through an electric field can be intercepted by a gaseous flow. The intercepted ions are of one polarity, insuring selective ion injection. Two types of injector units were investigated. One was a molecular ion device which produced ions directly from the carrier gas, and the other created larger sized ions, resulting in an aerosol flow. The latter consisted of passing saturated steam through a corona discharge and injecting it into an air stream. In order to aid the injection process, the wake of a cylinder in the air stream was utilized in both cases. Most of the work done here was devoted to the design and testing of the aerosol flow device. The degree of success was moderate.

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